Changes in Weight Distribution and Subsequent Biomechanical Characteristics Across Starting, Transitional, and End Phases of the Back Squat in Healthy Adults

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Abstract: The back squat is a common exercise used in strengthening and conditioning as well as activities of daily living. P**urpose:** Determine weight distribution in all phases of the back squat, kinematics and muscle forces of the vastus lateralis and vastus medialis at the starting, transition, and end points of the exercise. **Methods:** 27 healthy, asymptomatic individuals volunteered to participate in performing back squats for the study. Height (cm), weight (kg), Q-angle, and shoulder width were measured before the back squat was performed. They then completed 3 sets of 3RM and 5 sets of 1 repetition at 65 percent of their 3RM. Data was recorded during the squats using the TekScan HR mat, EMG surface electrodes, and electric goniometers. **Results:** Sample t test revealed significant weight shift on the left side compared to the right across all phases of the back squat ($p<.05$). Weight distribution on the right was significantly different among the three phases ($F_{2,50}=5.091$, $p=0.010$), and the end phase was significantly lower than the transitional phases on the right side ($p=0.024$). Weight distribution was significantly different during all three phases on the left ($p=0.002$, $F_{2.50}= 6.772$) and significantly higher at the end phase on the left side ($p=0.010$). Vastus medialis and lateralis muscle force increased significantly during ascending phase. **Conclusion**: These findings suggest that the transition phase is the most important phase of the squat in terms of maintaining consistency with weight shift, and that weight distribution is not necessarily equal between lower extremities even in a healthy, asymptomatic population. This study lends itself to future studies focusing on symptomatic participants as well as further definition and study of the transitional phase of the back squat.

Introduction

The back squat is a common closed chain strengthening and conditioning exercise utilized in the athletic population for core and lower extremity strengthening. Not only is the back squat common in the high performance athlete population, it is a common activity of daily living that requires the coordination of numerous muscle groups including: the quadriceps, hamstrings, gastrocnemius, gluteus maximus, abdominals, and spinal erectors. [1-3] When performed correctly, squat related injuries are uncommon.[3,4] The back squat can be broken down into several components: starting point, descending phase, transitional phase, ascending phase, and end point. During the starting point of the back squat, full hip and knee extension occur with toe angles varying depending on preferential squat form. During the descending phase, hip and knee flexion occur equally until the desired squat depth is obtained, eccentrically controlling the descending weight with co-activation of quadriceps, hamstrings, and activation of gluteus maximus, abdominals, and spinal erectors muscles.[2] Squats can be performed at a variety of depths, and generally measured by the degree of flexion at the knee. Quadriceps, hamstrings, and gastrocnemius activity increases as knee flexion increases providing sufficient support to avoid injury in healthy knees during the squatting motion.[5] There are numerous studies that have analyzed the various components of the back squat as a sagittal plane movement; assessing ankle, knee, and hip joint kinematics and also assessing the bilateral lower extremity differences across multiple components of the back squat.[5-7] One study assessed the influence of asymmetrical weight distribution in quiet standing, and how that influenced asymmetrical vertical ground reaction force and barbell tilt during the back squat, finding that individuals who stand with a greater asymmetrical weight distribution demonstrate greater asymmetrical ground reaction force.[7] However, this study did not assess asymmetrical ground reaction force across multiple phases of the squat to determine where the asymmetry occurs.

A component of the squat movement that has been researched very little is the transitional phase: the phase in which one must generate enough force to slow the descending phase and initiate forces to begin the ascending phase once the desired squat depth has been reached. One previous study found that EMG values of the vastus lateralis, vastus medialis, gluteus maximus, and rectus femoris measured highest during the beginning portion of the ascending phase [8], supporting the notion that the transitional phase is a key component of the back squat and requires more research as to the joint kinematics that occur during this time.

Previous studies have assessed the biomechanical changes that can occur following ACL reconstructions, such as asymmetrical lower extremity loading and altered weight bearing during squatting and changes in muscle recruiting during squat activities. [9,10] However, no previous studies have assessed if there is an asymmetrical weight shifting between the lower limbs across various positions during the back squat that can be considered normal in the asymptomatic population. No previous studies have assessed what could be considered a normal asymmetrical weight shifting in males and females during the back squat.

Therefore, the purpose of this study was to analyze and quantify the changes in weight distribution between the two lower limbs and muscles forces of the vastus lateralis and vastus medialis across three sequential positions of the back squat: starting, transition, and end positions. This study also hypothesized that the changes of weight distribution may impact the kinematic variables and muscle forces between two lower limbs during the back squat in healthy, asymptomatic adults. This study was performed as a preliminary study to examine the normal weight shifting patterns in healthy males and females. This study can be applied to future studies to examine asymmetrical weight distribution and weight shift in individuals who have knee pain or following knee injuries. This question has clinical relevance because if it can be determined that there is a normal amount of weight shifting that occurs between the lower limbs, abnormal weight shifting can be identified and addressed to avoid potential knee injuries or during rehabilitation after knee injuries have occurred.

Methods

Participants

This study included 27 healthy individuals whose average age was 23.46 years for females and 26.78 years for males in San Angelo, Texas area. Participants were divided between male and female (14 and 13 respectively) subjects. Patient demographic information is included in Table 1.1 below. Inclusion criteria for participants were that the participants were free from significant lower extremity injury, could adequately perform a squat to 90 degrees with feet positioned at shoulder width apart, and had abstained from lower extremity exercise for 48 hours prior to the study. Exclusion criteria for participants included having knee pain at the time of the study, inadequate range of motion at the ankle, knee, or hip joints, a recently sustained lower extremity injury, or inability to perform squat with the proper body mechanics.

Table 1- Demographics of Participants

	Female (n=13)	Male (n=14)
Average Age (years)	23.46 (1.2)	26.78 (4.32)
Average R Lower Extremity Q Angle (degrees)	14.07 (4.63)	13.46 (3.35)
Average L Lower Extremity Q Angle (degrees)	13.79 (3.6)	11.5 (2.35)
Average Height (cm)	168.24 (7.89)	178.53 (7.82)
Average Weight (kg)	63.29 (5.94)	81.89 (10.46)
% Participants- R Leg Dominant	100%	71%
% Participants- L Leg Dominant	0%	29%

Procedures

Before performing the back squat trials, the Q-angle was measured in supine using a standard goniometer for each lower extremity using the anterior superior iliac spine, the mid-point of the patella and the tibial tuberosity as landmarks. The participant was then weighed in kilograms, and shoulder width was measured in centimeters. In order to normalize the various widths of shoulder according to each participant, the shoulder width was operationally defined based on the distance between the right and left acromion. Participant foot arch type was assessed and categorized as low, normal, or high based upon foot contact and appearance on the Tekscan.

The back squat was performed barefooted (to minimize the effect of heel height and cushioning of shoes) and without the use of a weight belt. Three trials were performed at a maximal weight determined by their 3 repetition maximum, followed by five trials performed at 65% of the maximum weight. The back squat was performed at a rate of three seconds for the descending phase and three seconds for the ascending phase; counted out loud by a spotter. There was no bouncing allowed at the bottom of the squat, and it was to be performed in a smooth and consistent manner. Surface electrodes of a wireless telemetric system (Biometrics Ltd, Ladsmith,VA, USA) were applied to measure muscle activities of the VMO and VL of both lower extremities during the back squat. Electric goniometers of a wireless telemetric system (Biometrics Ltd, Ladysmith, VA, USA) were attached to the lateral side of each lower extremity using the head of the fibula for consistent placement.

The researchers used participant shoulder width to line up feet on the Tekscan HR mat (Tekscan, Inc., South Boston). The second toe was aligned at an even distance to the width of the acromion. Researchers placed a tape mark on the Tekscan mat for alignment, and the feet were aligned in the frontal plane by aligning the right and left fifth metatarsal heads with one another. If the participant's shoulders were too broad to be properly aligned on the Tekscan, the farthest width was used for data collection at a distance of 48.7cm. The researchers also ensured that the calcanei were in line with the 2nd digit before allowing the patient to begin the warm up set. Squat instructions during the warm up and subsequent phases of data collection were as follows: barbell should be resting comfortably on the shoulders with a tight supinated grip on the bar. Hand placement was determined by having the participant grip the bar with their thumbs extended to be touching their acromion for consistent hand placement during each trial. Participants were instructed to squeeze their shoulder blades together and downward for proper squat form. Toes remained pointed forward the entire trial. Squat movement was initiated by pushing hips backwards followed by bending the knees while continuing with hip motion. Participants were instructed to perform the squat until their thighs were parallel to the ground to ensure 90 degrees of knee flexion at the bottom of the squat. Knees remained in line with toes at all times.

The warm up set began by researchers bringing an un-weighted bar (12.72 kg) to the subject and placing the bar on the subjects back and aligning hands so that the subject's thumbs were touching their acromions. The subject then performed 3 sets of 5 repetitions, in proper foot alignment, with a spotter providing counting for the pace of the squat. The squat pace was three seconds for the descent and three seconds for the ascent. The bar was removed at the end of each trial in all three scenarios to allow the patient to rest. Thirty seconds were allowed between warm up sets. The bar was then removed and the subject was allowed to step off the Tekscan mat and rest for another 30 seconds. Researchers then put weight on the bar based on the subject's estimate of maximal effort of a three repetition maximum. The subject was then properly realigned on the mat and the weighted bar was brought to them and aligned on the subject's back by two spotters on each side of the bar. Three maximal squat trials were performed and followed by 5 submaximal trials at 65 percent of the weight of the maximal trials. Thirty seconds were allowed between trials while the subject remained on the mat in proper foot alignment.

Reliability coefficient for intra-tester reliability for using a standard electro-goniometer to measure knee flexion in standing was found to be .87-.88 using specific guidelines for electro-goniometer alignment.[11] In a study done by Zammit, Menz and Munteanu, the reliability of the Tekscan MatScan system was found to be moderate to good with intra-class correlation coefficients ranging from .44-.95 for measurement of plantar forces and pressures during barefoot walking.[12]

Statistical analysis

Prior to the parametric statistical analysis, the Shapiro-Wilk test was performed to confirm normality of all the kinematic and EMG variables during the back squat. Levene's tests were also conducted to check the homogeneity of all the dependent variables.

One-way repeated measure ANOVA was conducted to identify the changes of weight bearing on either side of two lower limbs among starting, transition, and end positions during the back squat. For weight shifting between the lower limbs during the back squat, both right and left lower limbs were compared at each sequential position using two tailed paired t-tests. All statistical analyses were calculated using IBM SPSS statistics 21 (Chicago, Illinois). P value was set at 0.05 to determine the significant difference.

Results

1. *Weight distribution between the right and left lower limbs across starting, transitional, and end position of the back squat*

A two tailed paired samples t test revealed significant weight shifts on the left side compared to the right side across starting, transitional, and end position of the back squat ($p < 0.05$). Please refer to table 2. One-way repeated measure ANOVA revealed that weight distribution on the right side of the lower limbs was significantly different among three different phases of the back squat ($F_{2, 50} = 5.091$, $p = 0.010$). The Bonferroni adjustment for multiple comparisons showed that the weight distribution of the end phase was significantly lower than the transitional phase of the back squat on the right side ($p = 0.024$). Weight distribution on the left side was also significantly different among the three different phases of the back squat ($F_{2, 50} = 6.772$, $p = 0.002$). The Bonferroni adjustment showed that the weight distribution of the end phase was significantly higher than the transitional phase of the back squat on the left side ($p = 0.010$). In addition, one-way mixed ANOVA was used to identify the effect between male and female adults, but there were no significant differences regarding weight distributions across starting, transition, and end positions of the back squat.

2. *EMG variables*

A two tailed paired samples t test showed that muscle forces of both vastus medialis and lateralis significantly increased more during the ascending phase than the descending phase of the back squat ($p < 0.05$). Please refer to Table 3. With respect to either side of the lower limbs, there were no significant differences between vastus medialis and lateralis during the descending or the ascending phase of the back squat ($p > 0.05$).

3. *Knee joint kinematics*

A two tailed paired samples t test showed that the Q - angle of the right limb was significantly higher than the left side while a supine position and time for the descending phase was also significantly prolonged than time for the ascending phase of back squat ($p < 0.05$). Please refer to table 3.

Table 2. Weight distribution (%) between the right and left lower extremity across the three sequential positions (starting, transitional, and end) of the back squat. Mean (SD).

	Right side	**Left side**	**Significance**
Three sequential positions			
Starting (%)	47.011 (3.432)	52.989 (3.432)	p = 0.000
Transitional (%)	48.094 (3.592)	51.906 (3.592)	p = 0.011
End (%)	45.782 (3.833)	54.533 (4.000)	p = 0.000

Table 3. Comparison of the descending and ascending phases on EMG variables and knee joint kinematics during the back squat. Mean (SD).

	Paired samples t-test		
	Descending phase	**Ascending phase**	**Significance**
EMG variables			
The peak amplitude of vastus medialis on the right side (mV)	0.321 (0.157)	0.357 (0.173)	p = 0.039
The peak amplitude of vastus lateralis on the right side (mV)	0.279 (0.095)	0.323 (0.109)	p = 0.002
The peak amplitude of vastus medialis on the left side (mV)	0.294 (0.121)	0.341 (0.146)	p = 0.000
The peak amplitude of vastus lateralis on the left side (mV)	0.271 (0.103)	0.308 (0.094)	p = 0.000
Knee joint kinematics			
The length of time (sec)	2.357 (0.354)	2.074 (0.392)	p = 0.000
Angular velocity on the right side (°/sec)	40.080 (8.434)	46.307 (12.497)	P = 0.000
Angular velocity on the left side (°/sec)	40.505 (8.658)	46.505 (11.794)	P = 0.000

Discussion

We hypothesized that there would be an asymmetrical weight distribution that occurs across the three sequential positions (starting, transition, and end) during the back squat in healthy adults. The other hypothesis was that the changes of weight distribution may impact the kinematic variables and muscle forces between two lower limbs during the back squat in healthy adults.

This study presented a significant difference of weight distribution between left and right lower limbs during the back squat at all points (starting, transition, and end). There was found a consistent asymmetrical weight shifting between the limbs until the transition point of the squat. Even more interesting, was after the transition point, there was a significantly greater asymmetry of weight shifting between the left and right limbs to the end of the squat with the majority of participants shifting from the right to the left. 85% of our subjects were right leg dominant demonstrating that majority of participants shift their weight from their dominant to their non-dominant leg. The four subjects with a left dominant limb followed a similar pattern of shifting weight from their left lower extremity to the right lower extremity. EMG activity of the vastus lateralis and vastus medialis resulted in a significant difference between the ascending and descending phases of the squat with more activity in the ascending phase. However, the ratio of muscle activation between vastus lateralis and vastus medialis remained near 1.0, on average, across all participants during the back squat. This study found there to be a significant difference between the ascending and descending phases for knee joint kinematics, which included the length of time of each phase and angular velocity at the knee for the phase. The descending phase was found to be significantly longer than the ascending phase, despite study design, which included the researcher providing verbal cues to the subject by counting out loud in an attempt to standardize each phase (descending and ascending) to three seconds each. This study also found there to be a greater angular velocity during the ascending phase. Gender did not have a significant effect on any of the previously stated variables in this study.

There was a significant difference of combined vastus lateralis and vastus medialis activation between descending and ascending phases with the ascent phase having greater overall EMG activity. It has been stated in a previous study that the EMG values for the ascent phase were 32% greater than those during the descent phase.[8] Following maximum muscle activity early in the ascent phase, muscle activity decreased as the subject extended the knees and hips to rise back to the starting position.[8] Another study states that the concentric phase of the squat had more EMG activity of the quadriceps and hamstrings than the eccentric phase of back squat.[13] This study is the only study that has included measurements of the transition phase. This transition phase is objectively the most difficult portion of the squat due to these EMG findings. This information can be correlated with the increased change in asymmetry of the weight shifting at the transitional phase discussed earlier. This suggests that the transition point is critical in determining an individual's ability to maintain consistency with weight shifting. The transition phase requires the muscles to transition from an eccentric contraction to a concentric contraction and overcome the weight of the barbell as well as gravity.

There was also a significant difference in the length of time and angular velocity between the descending and ascending phases of the squat with angular velocity being greater on the ascending phase. This is directly correlated with the length of time of the squat being less on the ascending phase than descending phase.

A study by Martins et al stated that 55% of healthy subjects demonstrated asymmetrical weight-bearing distribution during static standing.[14] While this study and the study mentioned above measured weight shifting during two different actions, standing and back squatting, the data shows that healthy individuals tend to not equally distribute their weight during stance or during squatting activities. In another study by Impellizzeri et al, they discovered that there are strength and weight distribution differences between the lower limbs of healthy individuals when performing squats and vertical jumps.[15] Regarding muscle forces and asymmetry, Chmielewski stated that though an association has been found between asymmetrical quadriceps strength and asymmetrical loading during a squat, it is not known whether the loading asymmetry preceded the quadriceps strength asymmetry or vice versa.[16] This study is important for establishing the basis for other studies to research the transitional phase of the back squat in healthy adults and the critical kinematic changes that occur. Future studies will also be able to use this data as a reference for normal weight shifting ratios in healthy adults during a back squat.

The first limitation of this study was the size of the Tekscan mat used to calculate weight distribution between the right and left lower extremity. To normalize the study parameters for each participant, each participant was required to stand with feet at shoulder width apart. This was a limitation for taller individuals and males with broad shoulders due to the Tekscan mat measuring 48.77 cm. The second limitation of this study was the toe angle required due to the size of the Tekscan mat. Participants were required to keep a forward toe position to maintain consistency across all subjects for squat form and for their feet to remain on the Tekscan mat. In future studies, the methods used for this study can be applied to various squat forms, such as wide stance, outward toe angle or squats to various depths, to assess asymmetrical weight shifting. The third limitation of this study was the use of only healthy subjects in obtaining data. Comparing subjects with lower extremity pathologies with healthy subjects could potentially reveal more clinically relevant data. Evaluating and treating a lower extremity loading asymmetry presents unique challenges to clinicians. Forces cannot be readily visualized, and most clinics do not have the expensive equipment (ie, force platform and motion capture system) to measure kinetics or technical staff to operate the equipment.[16] The limitation is that due to subtle, yet significant asymmetrical weight shift that occurs between lower extremities, it is difficult for a clinician to visualize this weight shift without video equipment. This study does bring to a clinician's attention the need to assess what is occurring during the transitional phase of the back squat, however a continuation of this study would be beneficial to further define the biomechanical and joint kinematics occurring during this phase.

Opportunities for Future Study

Future studies should compare our findings to various symptomatic populations to observe the transition phase in a symptomatic population. This study could be compared to individuals that are status post ACL reconstruction, individuals with patella femoral pain, or those with visible muscular imbalances. Comparing this study to symptomatic populations will help to future define what can be considered a normal amount of weight shifting between the lower extremities. This information could enlighten and define the concept of the transition phase, as previous studies have not assessed or defined this particular phase of the back squat. Future studies could also help further define the biomechanical and kinematic changes that occur during the transitional phase and how this phase is affected due to symptomatic factors (i.e muscular imbalance, trauma, or post-operative deficits). As there is no research specifically defining the transition phase, future studies should focus on determining how long this phase occurs as well as anterior-posterior weight shifting that may occur.

Conclusion

While the back squat is a well-researched functional activity, this study aims to provide information on a phase of the squat that has been researched very little: the transitional phase. This study also aimed to provide initial information on asymmetrical weight shifting that occurs in healthy males and females. We found that the majority (90% of subjects) shifted their weight from one lower extremity to the other between the transitional and end-point of the squat. Further study needs to be conducted to determine if the hypothesis of this weight shifting being normal in healthy males and females can be asserted with confidence. Further study will also help to define when this asymmetrical weight shifting becomes abnormal and should be addressed at the clinical level. This is an especially important clinical question as abnormal asymmetrical weight shifting could potentially be the result of or lead to pathology of the lower extremity. Finally, further understanding of the biomechanical and kinematic changes that occur during this phase could help coaches, physical therapists, and other clinicians when assessing subjects for proper squat form.

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